OPEN ACCESS

COMMENTARY

The Innovation Materials

From structural obstacle to tailored bisphenols: The condensation revolution in lignin valorization

Xu Fu,[1] Ling-Ping Xiao,[1,*] and Run-Cang Sun[1,*]

[1]Liaoning Key Lab of Lignocellulose Chemistry and BioMaterials, Liaoning Collaborative Innovation Center for Lignocellulosic Biorefinery, College of Light Industry and Chemical Engineering, Dalian Polytechnic University, Dalian 116034, China

*Correspondence: lpxiao@dlpu.edu.cn (L.X.); rcsun3@dlpu.edu.cn (R.S.)

Received: September 13, 2025; Accepted: November 12, 2025; Published Online: November 14, 2025; https://doi.org/10.59717/j.xinn-mater.2025.100172

Citation: Fu X., Xiao L. and Sun R. (2025). From structural obstacle to tailored bisphenols: The condensation revolution in lignin valorization. *The Innovation Materials* **3**:100172.

Lignin, as the only natural aromatic polymer, has always posed a major challenge in the field of biorefinery due to the difficulty in achieving its efficient and high value-added utilization. A fundamental defect of lignin lies in its uncontrollable condensation: in an acidic environment, protonation of C_α–OH followed by water elimination generates an electrophilic benzylic carbocation, which subsequently undergoes electrophilic aromatic substitution at electron-rich aromatic sites in lignin. The resulting C_α–Caryl bonds lead to extensive crosslinking, thereby increasing molecular weight and structural heterogeneity, which creates a barrier to depolymerization and other valorization processes. The core objective of the traditional condensation control strategy is to "prevent condensation". Methods such as C_α-acetal protection, phenolation, and oxidation, primarily focus on stabilizing the C_α site of the β-*O*-4 subunit, reducing the occurrence of disordered condensation reactions by inhibiting the activity of the C_α site.[1,2] Notably, a new strategy is gaining ground that harnesses lignin's inherent condensation tendency for high-value conversion rather than suppressing it. This paradigm shift is exemplified by the studies of Shuai's group[3] and Wang's group[4], who leveraged phenolic compounds to synthesize bio-bisphenols via C_α-phenolation, with Wang's group achieving a 48 wt% bio-bisphenols yield from wood via an aromatic migration mechanism. However, the C_α-phenolation exclusively takes place at moderate temperatures (80–150°C) in media containing strong acid (e.g., sulfuric acid) or high concentrations of a weak acid (e.g., 88% formic acid).[5]

Recently, a study by Shuai and colleagues, published in *The Innovation*, has further advanced this strategy. This work demonstrated a novel C_γ-condensation pathway, in which phenol reacted with the C_γ-position of a lignin intermediate (*p*-hydroxycinnamyl alcohol, CA) via a nucleophilic reaction under neutral or weakly acidic conditions and at temperatures between 150 and 250°C.[5] Specifically, the underlying mechanism of this approach involved two key aspects (Figure 1A): (1) phenol acted as a radical scavenger for lignin fragments, inhibiting radical-mediated condensation and facilitating the formation of CA; (2) excess phenol underwent condensation at the C_γ-posi-

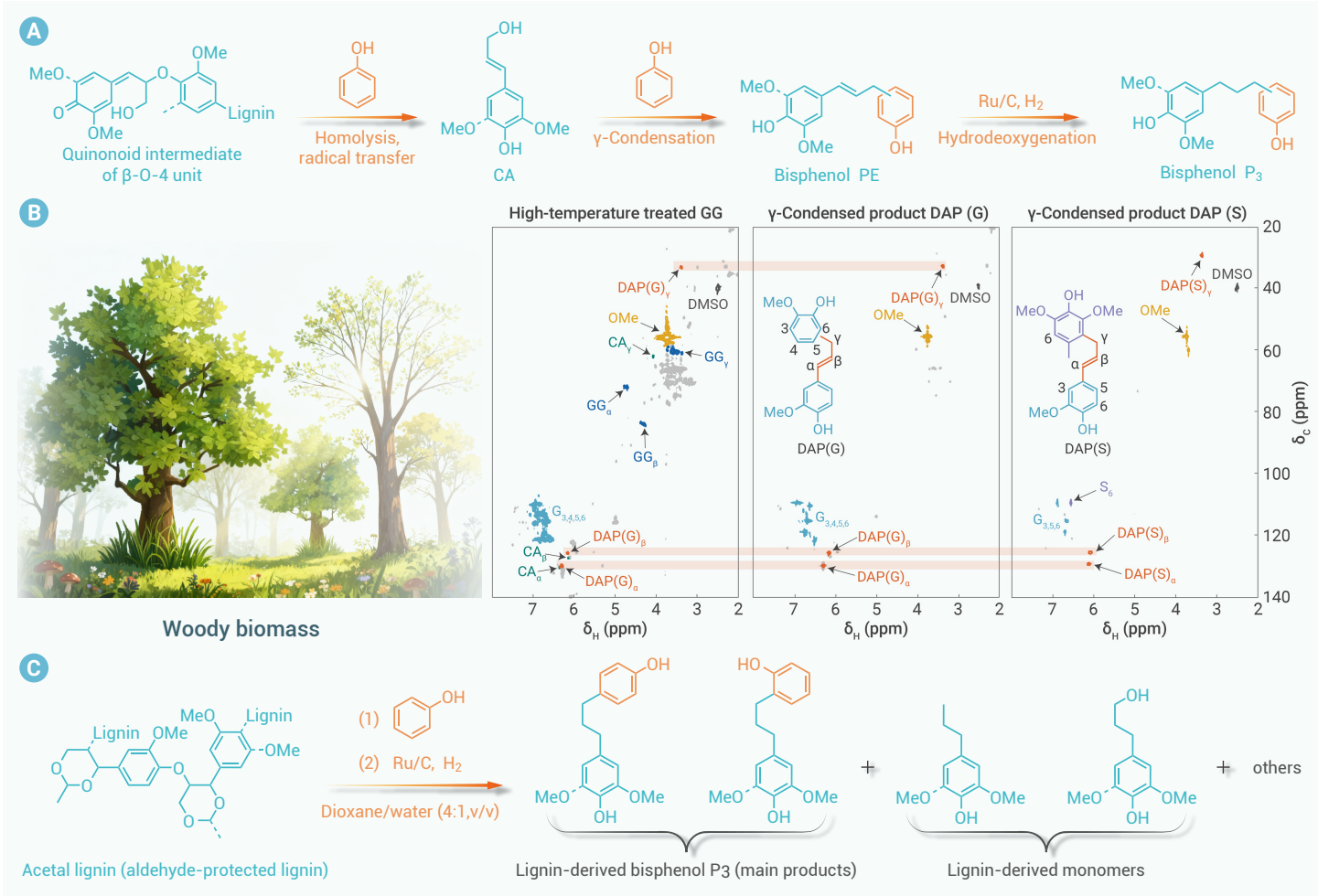

Figure 1. Pathways for synthesizing bisphenol P_3 from lignin (A) Synthesis pathway of bisphenol P_3 via C_γ-condensation. (B) 2D HSQC NMR spectra of GG products after the high-temperature treatment. (C) Conversion pathway of acetal lignin to bisphenol P_3 via a sequential phenolation and catalytic hydrogenolysis process.

tion of cinnamyl alcohol, forming a diarylpropene (DAP) skeleton. This intermediate could then be hydrogenated to yield bisphenol P_3.

More specifically, a free-phenolic β-*O*-4 model compound (GG) was initially employed as the substrate under high-temperature conditions (200–250 °C) in the presence of weak acid. Under these conditions, the degradation of GG primarily proceeded via homolytic cleavage, generating reactive radical species such as the CA. Subsequently, a process of repeated homolytic cleavage and radical recombination gradually converted unstable C–O bonds into more stable inter-unit C–C linkages. While phenol was introduced into the GG degradation system, the main product was bisphenol PE, along with a phenolic coupling byproduct (PP), formed via radical coupling of phenol molecules. The generation of PP indicated the involvement of radical transfer processes, suggesting that phenol acted as a radical scavenger by capturing the reactive CA species. Increasing the phenol concentration effectively enhanced the conversion of GG, since scavenging the radicals disrupted the equilibrium between homolytic cleavage of β-*O*-4 bonds and radical recombination, thereby promoting both the cleavage and the formation of CA. Notably, in the absence of phenol, GG degradation involved C_γ-condensation via a γ-carbocation (CA^+) with its own aromatic ring, leading to the formation of DAP, as shown in Figure 1B. While excess phenol was introduced, its aromatic ring acted as a nucleophile and preferentially reacted with CA^+, replacing the native lignin's aromatic ring. The electron-rich aromatic ring of phenol facilitated C_γ-arylation with CA^+, resulting in the formation of PE in yields ranging from 10.4% to 58.1%. This confirmed successful condensation between phenol and the γ-carbon of CA. Subsequently, the catalytic hydrogenolysis of the reaction product of GG and phenol converted bisphenol PE into bisphenol P_3, achieving a maximum yield of 67.6%. The same pathway was also effective when using an acetylated GG. These results collectively indicated that excess phenol condensed with the γ-carbon of CA to form PE, which could be hydrogenated to yield bisphenol P_3.

Having successfully demonstrated the pathway using the β-*O*-4 model compounds, the authors bridged a critical gap by further validating the mechanism with actual lignin (aldehyde-protected lignin), as depicted in Figure 1C. Bisphenol P_3 was produced from acetal lignin prepared from Eucalyptus and Masson pine with molar yields of 35.2% (45.9 wt%) and 14.8% (18.2 wt%), respectively. In addition, a one-pot process using Eucalyptus wood was explored to combine phenolation and hydrogenolysis in a single step. However, the yield of bisphenol P_3 was relatively lower than that of the two-step method with a maximum yield of 22.3% from Eucalyptus lignin. Despite the lower yield, these results served as proof of the C_γ-condensation pathway concept and provided a promising foundation for future optimization.

The C_γ-condensation pathway has significant potential to enhance lignin's industrial applications across multiple aspects. In terms of product structure, it successfully constructs a customizable 1,3-diarylpropane skeleton. Regarding process compatibility, the weakly acidic or neutral reaction environment required by this pathway is directly compatible with mainstream biomass pretreatment systems, such as dilute acid, organosolv, and hydrothermal treatments, effectively overcoming the technical issue of equipment corrosion under strongly acidic conditions. Notably, a molar yield of 35.2% (45.9 wt%) for bisphenol P_3 products was obtained from Eucalyptus lignin, demonstrating a viable route for the production of value-added aromatic compounds from lignocellulose. Furthermore, lignin-derived bisphenols can be further converted into bio-based polycarbonates and epoxy resins, or hydrogenated to afford high-energy-density aviation fuels, thereby providing foundational support for building a circular economy.

However, translating these achievements into industrial applications entails addressing some challenges. For instance, the economic constraints stem from the production process: it requires twice the mass of phenol as lignin, and both phenol recovery and bisphenol P_3 separation are energy-intensive processes. Furthermore, the process also faces a significant limitation in substrate adaptability. The conversion yield for Masson pine lignin (14.8%) is considerably lower than that of Eucalyptus lignin (35.2%). Addressing this issue requires developing tailored catalysts for various lignin or designing more universal catalytic systems. Similarly, the reaction pathway lacks generality by relying entirely on the nucleophilic activity of phenol. It remains unclear whether the strategy can be extended to lignin-derived phenols (e.g., vanillin) or incorporate nucleophiles such as amino acids to construct nitrogen-functionalized bisphenols.

Overall, to promote the industrial scale of lignin condensation technology from the laboratory stage, future research should focus on following aspects: (1) developing novel arylation reagent systems, with the core objective of reducing dependence on phenols while balancing sustainability, environmental friendliness, and economic viability; (2) optimizing catalytic depolymerization strategies and advancing toward tandem processes to achieve high-yield, high-selectivity production of bio-based bisphenols; (3) deepening research into the structure-activity relationships of bisphenols, ensuring performance advantages in end-use applications through molecular design, and prioritizing assessment of product biotoxicity and environmental hazards. Accordingly, it is critical to emphasize that life cycle assessment (LCA) can be integrated at the earliest stages of technology development. LCA is not a technical barrier but a decision-making tool supporting sustainable industrialization. By quantifying the environmental footprint across the value chain, LCA provides critical data for screening and optimizing technological pathways. In other words, this approach guides eco-friendly process development from the outset, thereby reducing industrialization risks and advancing the circular bioeconomy.

In summary, Shuai and colleagues' work not only revealed a novel C_γ-condensation pathway but also systematically elucidated the lignin condensation mechanism under high-temperature conditions. These insights provided a key theoretical foundation and a new design strategy for targeted lignin transformation. Such understanding enables coordinated control of mesothermal C_α-condensation and high-temperature C_γ-condensation pathways, enabling on-demand molecular structure customization. By turning structural constraints into synthetic advantages, this strategy ushers in a new era of "engineered lignin condensation". Therefore, we call for more research into control strategies for lignin condensation. This will pave the way for the transformation of lignin from a biorefinery waste to green platform chemicals, enabling the replacement of fossil-based bisphenol A with tailored lignin-derived aromatics. This replacement would mark a historic turning point for sustainable materials production in a carbon-neutral economy.

REFERENCES

1. Lan W., Amiri M.T. and Hunston C.M. et al. (2018). Protection group effects during α,γ-diol lignin stabilization promote high-selectivity monomer production. *Angew. Chem. Int. Ed.* **57**:1356–1360. DOI:10.1002/anie.201710838
2. Rahimi A., Ulbrich A. and Coon J.J. et al. (2014). Formic-acid-induced depolymerization of oxidized lignin to aromatics. *Nature* **515**:249–252. DOI:10.1038/nature13867
3. Gong Z., Yang G. and Huang L. et al. (2023). Phenol-assisted depolymerisation of condensed lignins to mono-/poly-phenols and bisphenols. *Chem. Eng. J.* **455**:140628. DOI:10.1016/j.cej.2022.140628
4. Li N., Yan K. and Rukkijakan T. et al. (2024). Selective lignin arylation for biomass fractionation and benign bisphenols. *Nature* **630**:381–386. DOI:10.1038/s41586-024-07446-5
5. Huang L., Zhao C. and Gong Z. et al. (2025). Manipulation of lignin condensation pathways to produce different bisphenols from biomass. *The Innovation* **6**:100997. DOI:10.1016/j.xinn.2025.100997

FUNDING AND ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China (22278049, U24A20559 and 51961125207) and the Dalian High-Level Talent Innovation Program (2024RJ017). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.